Institutional Barriers to Renewable Power Integration and Emissions Reduction: An India Case Study
On-line Appendices

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APPENDIX A: SOLUTION SUMMARIES

Here we summarize the results of three key scenarios.

Base scenario summary

In the base scenario, we formulate a unit commitment model with transmission constraints. The models are run for each quarter. The results are presented below:

TABLE A.I. SUMMARY RESULTS FOR THE BASE SCENARIO

Quarter	Cost (USD Billion)	GWh Curtailed	GWh RE Generated	Load Lost (GWh) (% of total demand)
Quarter 1	5.82	0	33289	21 (0.007%)
Quarter 2	6.53	0	41524	116 (0.03%)
Quarter 3	5.10	0	50706	43 (0.013%)
Quarter 4	5.27	0	27588	23 (0.008%)

P scenario summary (Preference for in-state generation)

When states exercise preference (Equation 10 of the manuscript), curtailment and costs increase as a consequence. Costlier thermal power plants get pressed into service as a result of preference constraints. This also could have several impacts that vary on a case to case basis – (1) this constrains transmission network in a manner such that RE output from some states get curtailed, (2) in other cases, additional thermal power plants in various states allow better flexibility and hence absorb RE (which could have been otherwise curtailed) and also reduce load shedding.

TABLE A.II. SUMMARY RESULTS FOR THE P SCENARIO

Quarter	Cost (USD Billion)	GWh Curtailed	GWh RE Generated	Load Lost (GWh) (% of total demand)
Quarter 1	6.55	161	33128	251 (0.084%)
Quarter 2	7.25	109	41414	19 (0.006%)
Quarter 3	6.35	800	49905	139 (0.042%)
Quarter 4	6.19	223	27365	55 (0.019%)

The costs increase, indicating utilization of costlier generators that were either not generating or generating less in the base case. Preference constraint induces the states to switch on their in-state generators, despite these being costlier than other underutilized generation capacities in the system. Overall, curtailment also increases in all quarters. Quarter 3 (July-Sept) is the period with high RE generation. More than 10% of wind and solar generation is indicated to be curtailed in Karnataka in quarter 3. The curtailment declines to slightly above 4% in quarter 4 in Karnataka. Curtailment in quarter 2 is indicated in Odisha and in Odisha and Karnataka in quarter 1.

PR scenario summary (P scenario plus regulatory constraint)

There is an increase in costs with the addition of (Equation 11 of the manuscript) to the P scenario. As the regulatory constraint is imposed, there are a few costly generators that come on-line. We have kept the value of unserved energy (USD 66 / MWh) very close to the retail tariff. The cost of unserved energy (for the DISCOM) is not very high as these utilities tend to view load shedding as just the revenue loss and hence linked to the retail tariff. DISCOMs, in daily operations, do not consider the cost of load shedding in terms of economic loss. Therefore, the retail tariff tends to get compared with the variable cost of marginal generation required to be scheduled to meet this additional demand. Whether load shedding increases or not with a constraint's application depends on whether costlier generators are getting switched on. When costlier generators get switched on, the ability to meet unserved demand and absorb variations in wind and solar generation increases and hence load shedding decreases (quarter 1, quarter 3) in the PR case as against the P case. Load shedding happens either during morning hours (7-8 AM) or evening hours (4 – 8 PM), when the flexibility of on-bar generators plays a big role in mitigating load shedding because such flexible generation is able to absorb ramp-up of RE (morning) and ramp-down of RE (evening hours). Also, load shedding is indicated for atmost one-three contiguous hours rather than for extended durations.

TABLE A.III. SUMMARY RESULTS FOR THE PR SCENARIO

Quarter	Cost (USD Billion)	GWh Curtailed	GWh RE Generated	Load Lost (GWh) (% of load)
Quarter 1	6.66	158	33130	2 (0.001%)
Quarter 2	7.81	89	41434	53 (0.016%)
Quarter 3	6.70	824	49881	14 (0.004%)
Quarter 4	6.34	227	27360	153 (0.054%)

PRA scenario (PR plus legacy power purchase agreements)

With the application of power purchase (Equation 12 of the manuscript) to the PR scenario, costs, curtailment, and load shedding increase. In our model, main states that experience load shedding include Maharashtra, Odisha, Kerala, Bihar, Jharkhand. This corroborates with the load generation balance report 2019-20, where anticipated deficit to the extent of 3.5% in Maharashtra, 5.5% in Kerala, 8.8% in Bihar, 19.2% in Jharkhand, 12.2% in Odisha is reported. Actual deficit reported at all India level in 2019 was 0.6%.

TABLE A.IV: SUMMARY RESULTS FOR THE PR SCENARIO

Quarter	Cost (USD Billion)	GWh Curtailed	GWh RE Generated	Load Lost (GWh)
Quarter 1	6.71	183	33106	108 (0.036%)
Quarter 2	9.07	705	40818	9303 (2.70%)
Quarter 3	6.85	923	49782	48 (0.015%)
Quarter 4	6.60	267	27320	561 (0.196%)

APPENDIX B: DATA SOURCES AND ASSUMPTIONS

We used the own-generation and import data available on www.meritindia.in to compute estimates of domestic preference – this is simply the ratio of power procured through domestic sources. The intent is to show their impact on optimal dispatch, renewable energy curtailment, and load shedding. These estimates of preferences are at best indicative and could be refined with the systemic availability of longer time series. This is because actual preferences could vary depending on the availability of in-state generation resources each day. There are, however, some systematic patterns that can be observed from the data on www.meritindia.in. We have attempted to capture the same.

Assumptions about long-term power purchase agreements

DISCOMs purchase power through long-term power purchase contracts and in the short-term markets. The capacity of the central sector generating stations is allocated to various states. The allocated capacity of power plants to various states is provided on www.meritindia.in and has been collated from there. For the power plants where such data was not available on www.meritinida.in, the data was collected from the tariff orders of various state electricity regulatory commissions. Power plants, for which contract data was unavailable, have been considered merchant power plants in the model. The size of the data set does not permit us to present these data here but can be procured from the authors on request. Table B.I gives the percent of peak demand that states normally schedule from contracts. This is an average of schedules for typical days drawn from the Regional Load Dispatch Center (RLDC) websites:

1. Northern region: NRLDC:http://wbes.nrldc.in/csv/
2. Eastern region: ERLDC:https://wbes.erldc.in/ReportFullSchedule (select any buyer/seller and then select the details tab on the top to see Real Time Market (RTM) and Security Constrained Economic Dispatch (SCED) data)
3. Western region: WRLDC:https://wbes.wrldc.in/ReportFullSchedule (select any buyer/seller and then select the details tab on the top to see RTM and SCED data)
4. Southern region: SRLDC:https://wbes.srldc.in/ReportFullSchedule (select any buyer/seller and then select the details tab on the top to see RTM and SCED data)

TABLE B.I: PEAK POWER SCHEDULED AS % OF CONTRACT CAPACITY

States	% Power Scheduled from Contracts	States	% Power Scheduled from Contracts
Punjab	30%	Maharashtra	23%
Haryana	41%	Chhatisgarh	37%
Rajasthan	24%	Andhra P	23%
Delhi	39%	Telangana	28%
Uttar Pradesh	29%	Karnataka	24%
Uttarakhand	27%	Tamil Nadu	35%
Himachal	51%	Kerala	54%
Jammu Kashmir	67%	Arunachal P	70%
Bihar	95%	Assam	80%
Jharkhand	69%	Manipur	83%
Odisha	32%	Meghalaya	39%
West Bengal	34%	Mizoram	57%
Sikkim	70%	Nagaland	77%
Gujarat	32%	Tripura	75%
Madhya P	39%	Bhutan	0%

The figure for Bhutan (a separate country but tightly meshed with Indian electricity systems) has been arbitrarily assumed so that it does not restrict the model.

Regulatory cap on power purchase costs

In the tariff orders, State Electricity Regulatory Commissions (SERCs) approve the power purchase costs of the DISCOMs in their jurisdiction. Power purchase costs normally consist of fixed and variable costs. Since the model developed in this paper is based on the unit commitment model, only the variable costs approved by the SERCs were considered to impose a regulatory budget constraint on the power purchase by the DISCOMs. The average variable costs for various states considered in the model are presented in supplementary Table B.II.

TABLE B.II: REGULATORY CAP ON VARIABLE CHARGES FOR STATES

States	Cents/kWh	States	Cents/kWh
Punjab	4	Maharashtra	4
Haryana	4.63	Chhatisgarh	3.51
Rajasthan	4	Andhra P	3.33
Delhi	3.93	Telangana	2.91
Uttar Pradesh	3.12	Karnataka	5.13
Uttarakhand	3.72	Tamil Nadu	4.09
Himachal	3.39	Kerala	6.93
Jammu Kashmir	6.67	Arunachal P	2.76
Bihar	3.39	Assam	5.29
Jharkhand	3.52	Manipur	4.05
Odisha	3.45	Meghalaya	3.07
West Bengal	3.65	Mizoram	4.05
Sikkim	3.03	Nagaland	4.16
Gujarat	3.87	Tripura	2.88
Madhya P	4.35	Bhutan	6.67

Note: figure for Bhutan is an assumed number.

Input data for unit commitment model

Installed capacity: The installed capacity of various power plants has been sourced from www.meritindia.in. The data were also correlated with the capacities CEA thermal review and the report on the ramping capabilities of generators in India [1, 2].

Ramping up/down rates: In 2019, Power System Operation Corporation Limited (POSOCO) produced a detailed report on ramping up and ramping down capabilities of various thermal power plants in India [2].

Minimum up/ downtime: These data are unavailable. We have assumed 18 hours of minimum up/downtime for coal/lignite-fired power plants, 2 hours for gas-based power plants, and 1 hour for hydropower plants.

Variable costs of generation: These costs have been sourced from the www.meritindia.in website. For the power plants not available on www.meritindia.in, the data was collated from the tariff orders of SERCs [3]. (In the references an example of Punjab state is provided, similar data are also available for other states.)

Startup/shut down costs: These were not considered in the model. These costs are not available in the public domain and are not explicitly considered in scheduling decisions by the generators. Generating stations are paid variable charges for the scheduled quantum. Since the DISCOMs are required to pay only the variable charges for energy scheduled, the considerations of startup/shutdown costs do not alter scheduling decisions.

Renewable Energy and Hydro Profiles: Renewable Energy (wind and solar) generators have been aggregated at the state level. Profiles for wind and solar generation for various states were downloaded from www.renewables.ninja for various states of India. The actual availability of hydropower plants was obtained from the websites of Regional Load Dispatch Centers (RLDCs) for the central sector plants. Hydro availability for state-owned power plants was estimated based on the nearest central sector power plant.

State-level demand: State-level demand was scraped from www.vidyutpravah.in for 2019. We use k-means clustering at a quarterly level to identify the representative days for our simulations. The input vectors were 24 hourly demand. Five days were selected for the first quarter (January – March), four each for the second (April – June) and the third quarter (July – September) and five days for the fourth quarter (October – December). The number of similar days for each of these representative days are provided in Table B.III.

TABLE B.III: CLUSTERS AND NUMBER OF DAYS IN EACH CLUSTER

Cluster	Quarter	Number of Days
1	January - March	21
2	January - March	15
3	January - March	20
4	January - March	5
5	January - March	29
6	April – June	30
7	April – June	9
8	April – June	36
9	April – June	16
10	July - September	36
11	July - September	27
12	July - September	23
13	July - September	6
14	October - December	30
15	October - December	9
16	October - December	21
17	October – December	19
18	October – December	13

Transmission network data: The Indian transmission data from 132 kV to 765 kV has been aggregated at the state level. The model considers 29 Indian states and Bhutan connected by 60 transmission lines. The data are based on the study published in reference [4] by one of the authors.

REFERENCES

[1] *Performance Review of Thermal Power Stations*, Central Electricity Authority, New Delhi, India, 2019.

[2] *Analysis of Ramping Capability of Coal-Fired Generation in India*, Power System Operation Corporation Limited, New Delhi, India, 2019.

[3] *Petition No. 02 of 2019 Filed by PSPCL for True-up of FY 2017-2018, Annual Performance Review for FY 2018-19 and Approval of Revised ARR for FY 2019-20 and Determination of Tariff for FY 2019-20*, Punjab State Electricity Regulatory Commission, Chandigarh, India, 2019.

[4] D. Chattopadhyay, P. Chitkara, I. D. Curiel, and G. Draugelis, "Cross-border interconnectors in south asia: market-oriented dispatch and planning," *IEEE Access*, vol. 8, pp. 120361-120374, 2020.